Jet Formation from Rotating Magnetized Objects

G.S.Bisnovatyi-Kogan* N.V.Ardeljan†, S.G.Moiseenko ‡

Abstract

Jet formation is connected most probably with matter acceleration from the vicinity of rotating magnetized bodies. It is usually related to the mass outflows and ejection from accretion disks around black holes. Problem of jet collimation is discussed. Collapse of a rotating magnetized body during star formation or supernovae explosion may lead to a jet-like mass ejection for certain angular velocity and magnetic field distributions at the beginning of the collapse. Jet formation during magnetorotational explosion is discussed basing on the numerical simulation of collapse of magnetized bodied with quasi-dipole field.

1 Introduction

Matter outflow is observed in most astrophysical objects in the form of stellar wind, or collimated outflow (ejection) from young stellar objects, AGN and quasars, microquasars (galactic X-ray sources). Mechanisms of mass loss are connected with a radiative and/or electromagnetic acceleration. The last one, which is probably the best for producing collimated outflows, may work quasi-stationary, or may be connected with explosive events. Rotation is always present in compact objects, and formation of collimated jets results from the action of magneto-rotational phenomena.

2 Problem of collimation

During accretion and outflow of matter the relative dynamical action of magnetic field increases for a given element of matter. As was shown in [Schwartzman(1971)], the conservation of a magnetic flux during stationary accretion implies a dependence $B_r \sim r^{-2}$. At constant mass flux $\dot{M} = 4\pi\rho v_r r^2$ and free-fall velocity $v_r \sim r^{-1/2}$, the density increases as $\rho \sim r^{-3/2}$, and kinetic energy density $E_k \sim r^{-5/2}$. The growth of the magnetic energy density is faster

*Space Research Institute, Profsoyuznaya str. 84/32, Moscow 117810, Russia, E-mail: gkogan@mx.iki.rssi.ru

†Department of Computational Mathematics and Cybernetics, Moscow State University, Vorobjevy Gory, Moscow B-234 119899, Russia, E-mail: ardel@redsun.cs.msu.su

‡Space Research Institute, Profsoyuznaya str. 84/32, Moscow 117810, Russia, E-mail: moiseenko@mx.iki.rssi.ru

$E_m \sim B_r^2 \sim r^{-4}$. After equipartition $E_k \sim E_M$ is reached, it cannot be violated during subsequent accretion.

The outflow from rotating magnetized object contain azimuthal component of the magnetic field, which energy density decreases not faster than the specific kinetic energy of matter. For the outflow with constant velocity v_r in stationary spherical outflow the density $\rho \sim r^{-2}$, $B_\phi \sim r^{-1}$. In this conditions $E_k \sim E_m$, and the trajectories of mass outflow become more tightly spiraled, and finally the flow is becoming highly collimated with direction of the flow along the rotational axis [Heyvaerts and Norman(1989)], [Bogovalov(1998)]. We may say here about the universal magnetic collimation in the outflows from rotating magnetized objects.

The outbursts may be collimated at the very beginning. When jets are separated from the object of its origin the problem appears of preservation of the jet against its spherization during a motion in a rarefied medium. One of the plausible mechanism of jet preservation is a magnetic pinch collimation produced by an axial electrical current, suggested in [Bisnovatyi-Kogan et al.(1969)].

3 Jet formation by matter outflow from magnetized accretion disk

Accretion of matter with a large scale magnetic field into a black hole leads to formation of an accretion disk with a strong poloidal magnetic field. Models of non-rotating accretion disks, supported by magnetic field had been constructed in [Bisnovatyi-Kogan and Ruzmaikin(1974)],
[Bisnovatyi-Kogan and Ruzmaikin(1976)], see Figure 1.

Rotation of matter in such a disk is accompanied by generation of a strong electrical field, leading to particle acceleration and ejection of matter along magnetic field lines. Qualitative and phenomenological models had been considered in [Bisnovatyi-Kogan and Blinnikov(1976)],
[Blandford(1976)], [Lovelace(1976)]. Analytical self-similar solutions for jets and winds produced by centrifugally and magnetically driven mechanisms had been obtained in [Blandford and Payne(1982)], [Lovelace et al.(1991)].

Extensive numerical simulations have been done for construction of more realistic models of quasi-stationary jet formation from magnetized accretion disks. In the paper [Romanova et al.(1998)] numerical simulations have been done of dynamics of magnetic loops in the coronae of accretion disks. It was obtained that in presence of differential rotation the loops are opened in the inner parts of the disk, and opening of loops is followed by magnetically driven outflow from the disk. The outflow may be transient, consisting of small-scale outbursts from different loop opening, or may be steady, corresponding to outflow along the open field lines at the inner part of the disk, and showing some collimation. Computations of magnetocentrifugally driven winds had been performed in [Ustyugova et al.(1999)]. The stationary regime of the outflow was obtained by solution of time-dependent MHD equations, with a split-monopole poloidal

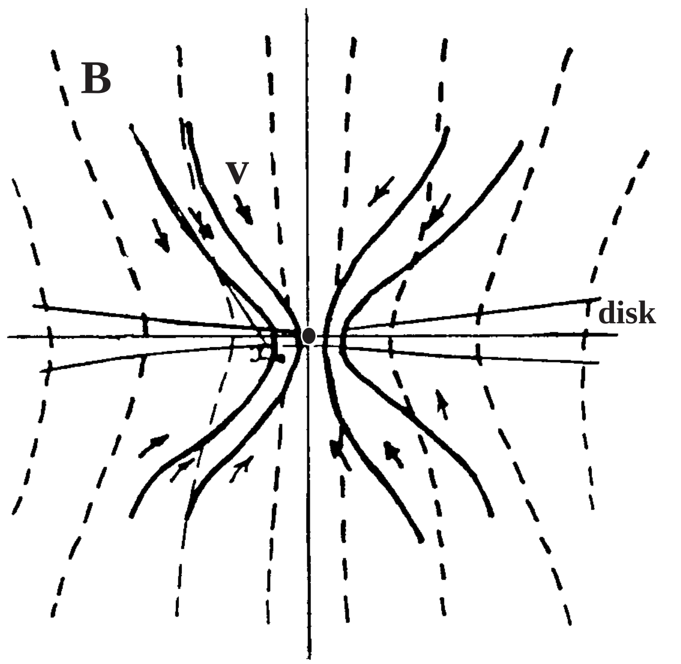

Figure 1: Schematic picture of magnetic field lines, obtained from the external uniform field by accretion of a non-rotating gas with infinite conductivity into a black hole. Dash lines are produced by the self-similar accretion flow with a sink in the equatorial plane. In reality the accretion gas is forming a disk in the equatorial plane, where matter is collected, and is moving into a black hole due to non-perfect conductivity. This motion is generating additional azymuthal currents in the disk, changing the external magnetic field. Solid lines give the self-consistent magnetic field structure with account of currents in the disk, from [Bisnovatyi-Kogan and Ruzmaikin(1976)].

field configuration frozen into the disk. Close to the disk the outflow is driven by the centrifugal force, while at all larger distances the flow is driven by the magnetic force, which is proportional to $-\nabla(rB_\phi)^2$, where B_ϕ is the toroidal field. The collimation distance over which the flow becomes collimated is much larger than the size of the sumulation region, so the obtained outflows are approximately spherical.

MHD simulation have been performed in [Ustyugova et al.(2000)] of Pointing outflows, where the mass flux is negligible and energy and angular momentum are carried predominantly by electromagnetic field in the form of MHD waves. As a result of time-dependent simulations a quasi-stationary collimated Pointing jet arises from the inner part of the disk and a steady uncollimated hydromagnetic outflow from the outer disk for a case Keplerian disk initially threaded by a dipole like poloidal magnetic field.

4 Magnetorotational explosions

Mechanism of magnetorotational explosion was suggested in [Bisnovatyi-Kogan(1970)], where amplification of the toroidal component of the magnetic field due to differential rotation leads to the transformation of a part of the rotational energy to the energy of the ejection. First numerical simulations devoted to the magnetorotational mechanism were made in [Le Blanc and Wilson(1970)], and investigated analytically by [Meier et.al.(1976)].

One of the most important parameters for this problem is relation of magnetic energy to the gravitational energy of the star: $\alpha = \frac{E_{\rm mag}}{|E_{\rm grav}|}$. 2-D simulations have been done in [Ardeljan et al.(2000)] for the initial values of the $\alpha = 10^{-2},\ 10^{-4}, 10^{-6}$. The computations have been performed using implicit Lagrangian scheme with triangle reconstructive grids, specially designed for astrophysical problems. Details of the definition of the initial magnetic field are described in the paper [Ardeljan et al.(2000)].

Initial magnetic field chosen for our simulations has quadrupole-like kind of symmetry (i.e. its "z"- component is equal to zero at the equatorial plane). As a result an ejection predominantly in the equatorial plane was obtained. The toroidal magnetic field grows with time and produces MHD shock which moves to the boundary of the star. Part of the matter of the envelope of the star (about 7% of the mass of the star) has radial kinetic energy larger than its potential energy and can be ejected. This ejected matter carries about 3.3% of the total energy of the star (see also the previous contribution). When the initial magnetic field have a dipole-like symmetry jet formation is possible as was first shown in calculations of [Le Blanc and Wilson(1970)]. Calculations with the initial magnetic field structure, similar to [Le Blanc and Wilson(1970)] have been performed using the same program as in [Ardeljan et al.(2000)]. The results are presented in Figures 2-4. The initial model (Fig.2, left) was constructed as a differentially rotating star with a quasi-dipole magnetic field (Fig.2, right), produced by toroidal currents ring situated at about 0.5 of the equatorial radius,

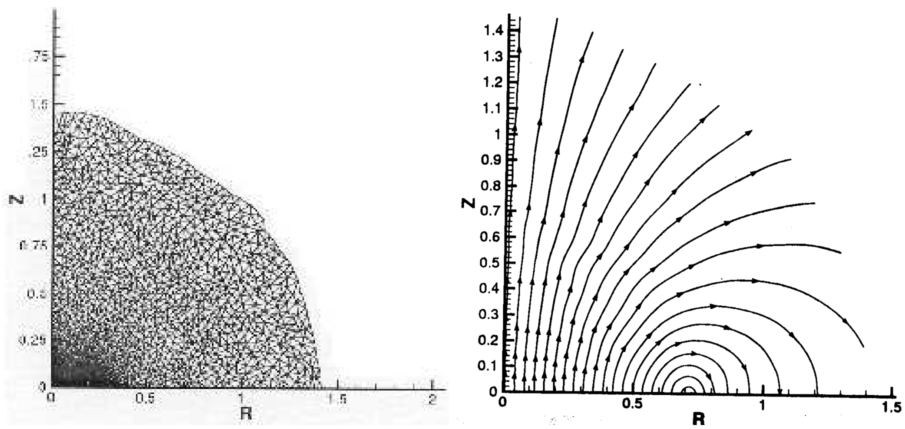

Figure 2: Lagrangian grid (left), and poloidal magnetic field distribution (right) in a stationary equilibrium differentially rotating star at $t_1 = 18.918451$, when the magnetic field was included into calculations.

where density was less than 0.1 of the central density.

The time is given in non-dimensional units, one unit of time is roughly equal to the time of crossing of stellar radius with the parabolic speed of the initial model. Initial distributions of the density and angular velocity are represented in Figure 3.

Magnetic field twisting produced strong toroidal magnetic field with local energy density of the order of the one of the matter. Absence of the radial component of the magnetic field in the equatorial plane led to formation of toroidal field rings at higher latitudes. The excess of the magnetic pressure produced a matter compression across the axis, and ejection of the matter in the direction attached to the axis. Density distribution and velocity field in the last calculational point with clear indication of formation of the ejection are represented in Figure 4.

5 Mirror symmetry braking of magnetic field in differentially rotating stars

There is a possibility of asymmetric MHD explosion, when we have asymmetric magnetic field amplification. One example of development of asymmetric picture was considered by [Bisnovatyi-Kogan and Moiseenko(1992)]. When the collapsing and exploding star has initially toroidal and poloidal fields of different symmetry: dipole poloidal and symmetric poloidal, or quadrupole poloidal and antisymmetric toroidal fields, formation of an additional toroidal field from the existing poloidal due to differential rotation leads to spontaneous breaking of the symmetry. Due to the asymmetry of the toroidal field during the explosion the outbursts could also become asymmetric, giving observational asymmetric

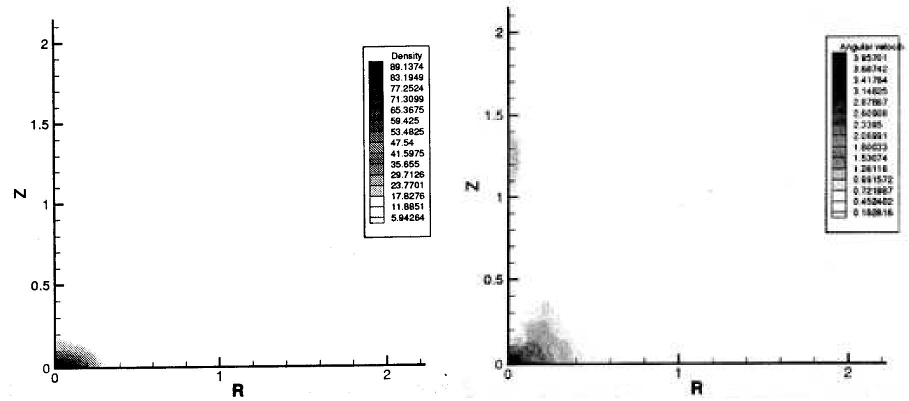

Figure 3: Density (left), and angular velocity (right) distributions at $t_1 = 18.918451$.

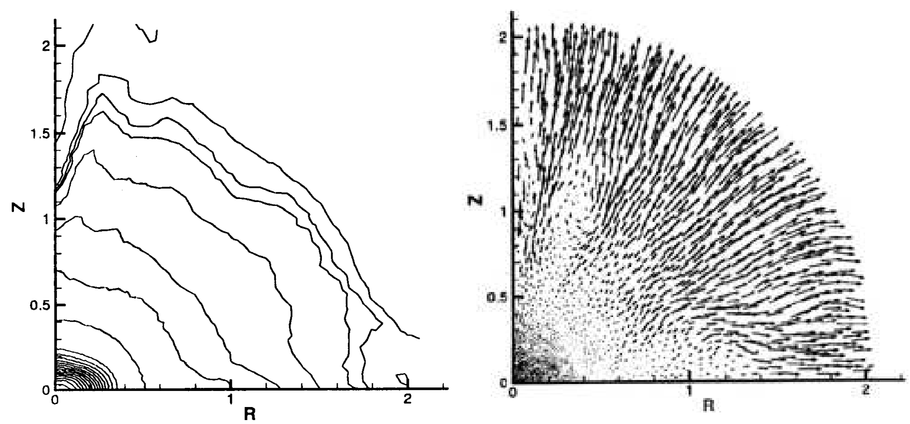

Figure 4: Density distribution (left) and velocity field (right) at $t = 30.947880$, when the mass ejection preferentially in the pole direction is formed.

or even one-side jets often observed in extragalactic jets, and may be in microquasars [Mirabel et al.(1992)], [Fender(1999)]. Another possibility of the asymmetry of the magnetic field was considered in [Wang et al.(1992)], where disk with the mixture of dipole and quadrupole fields was considered. Asymmetric magnetic field in the accretion disk may lead to appearance of asymmetric jets in stationary and non-stationary variants. In transient accretion disks, formed by tidal capture or destruction of the nearby star by a black hole, asymmetric magnetic field may be formed, and magnetorotational explosion in such disk may lead to the one side ejection.

Acknowledgments

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